An Optical Study On Different Profiles For Parabolic Solar Concentrators

AN OPTICAL STUDY ON DIFFERENT PROFILES FOR PARABOLIC SOLAR CONCENTRATORS (PTC)

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Abstract

The aim to realize more efficient solar concentrators, improves the research on the optimal configuration for the reflective surfaces. The optical behaviour of a parabolic trough collector is investigated depending on its particular shape outside the ideal conditions. A 2D ray-tracing model of the real systems was built taking into account the solar radiation and total misalignment errors σ up to 1.25°.
The computational analysis shows the relationship among the collection performance and the main geometrical parameters; different boundary conditions bring to consider different optimal configurations for the concentrator profile. For medium concentration ratios and non-ideal settings the more efficient parabolas are not characterized by a rim angle equal to 90°, which is the theoretical best value. Imposing constant good performances and a misalignment error of 0.25°, 0,5°, 0.75°, 1°, 1.25° respectively, a maximum concentration ratio near to 113, 71, 45, 35, 29 can be reached with the rim angle value that gradually varies from 104° to 112°.

Keywords: Parabolic trough concentrators, optical analysis, ray-tracing, concentration ratio.

Introduction

During the last decades the concentrating technologies for solar energy employment have gone on expanding all over the world in many different configurations [1-7]. There are some important advantages both for PV and CSP applications in respect to the flat solutions. Generally in the first case, using last generation devices, the conversion efficiency can be boosted up and also the raw material for cells can be reduced. For what concerning the CSP systems high temperatures can be reached increasing the energy amount of the heat transfer fluids.
The common concentrating layout requires the use of lens and mirrors and, in particular, the parabolic profile is one of the most widespread because of its construction properties and a reasonably good manufacture feasibility [8].
The optimization of the mirror surfaces design is important to characterize the entire solar energy conversion system because it is the most responsible of the radiation capture and collection. Then it becomes more relevant in non-ideal working conditions due for instance to the solar divergence and the scattering effects associated to the slope errors and the reflective surface properties.

1. Geometrical considerations

The solar concentrators can be modelled using the laws of Geometrical Optics. This permits to consider light as rectilinear segments interacting with reflective and diffractive surfaces. Therefore the main parameters of a parabolic mirror and its respective absorber are obtained by trigonometric steps imposing some boundary conditions [9].
In fig. 1 we show the characteristics of a parabolic collector (cross section) for CSP applications:

- d is the absorber diameter;
- c is the chord of the collector;
- f is the focal length of the parabola;
- φ is the rim angle of the reflective geometry;
- σ is the misalignment angle (tilt angle) between the direction of the incoming rays and the collector.

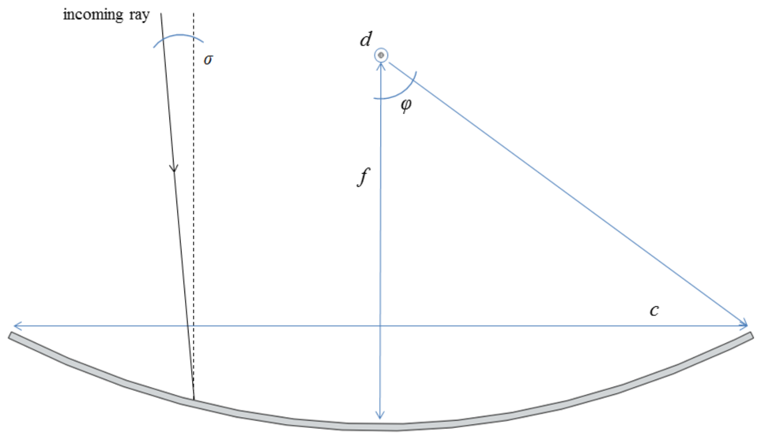
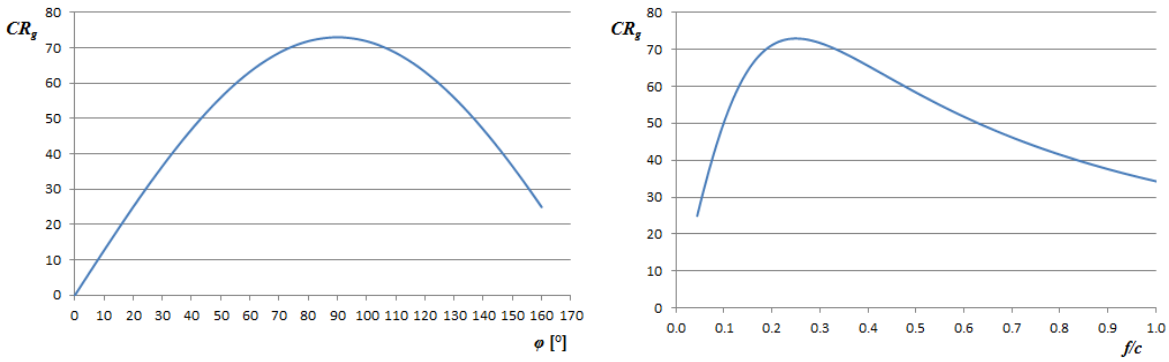


Fig. 1 - Main characteristics of a parabolic concentrator.

Then we can define the geometric concentration ratio as:

$$CR_g = \frac{c}{\pi d} = \frac{\sin \varphi}{\pi \sin \sigma}$$

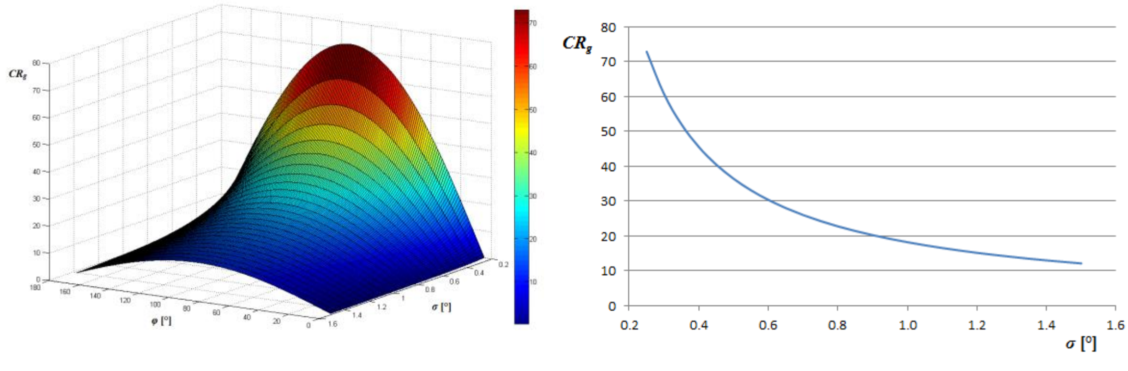
Regardless of the misalignment conditions σ, the maximum value is always reached when the rim angle is 90° and *f/c* is 0.25. The specific trends for the tilt angle typical of the solar divergence (0.25°) are shown in Fig.2.
The curves can be explained considering the irradiated portion of the absorber surface and the reflected rays path. When the rim angle under 90° the pipe is not completely immersed in the light beam and it does not work to its full potential. On the other hand if the rim angle is increased above 90° the rays path rapidly becomes longer and the rising in the absorber diameter is wider than the collector chord growth.



(a) (b)

Fig. 2 - The geometrical concentration ratio as a function of the rim angle and *f/c* ratio. The solar divergence (σ = 0.25°) was considered.

Of course the misalignment angle is very relevant too. Increasing the tilt effects, the geometric concentration ratio drops quickly in particular for the higher achievable values as it is seen in the plots of Fig. 3.



(a) (b)

Fig. 3 - (a) The geometric concentration ratio as a function of the rim angle and the misalignment angle. (b) The same curve for the concentration ratio maximum value (φ = 90°).

2. The computational model

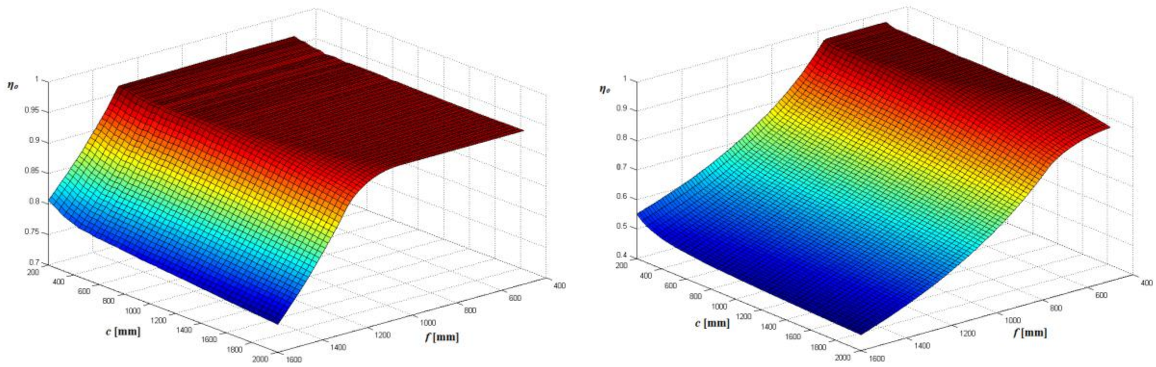
The previous considerations give the relationships among the geometrical parameters for a fixed tilt angle imposing that all the reflected rays reach the absorber circumference. In the next sections we report a sensitivity analysis varying the geometrical dimensions and the boundary conditions step by step.
First of all an optical model was realized based on a commercial software. All a 2-D geometry was constructed comprising a parabolic mirror with 95% of reflective index and a circular absorber detector. Then a flat source was set to simulate the sun and a radiation density was fixed at 1000 W/m^2. We imposed the rays to have a normal direction in respect to the emitting surface introducing an uniform distribution range within a plane angle. With this conditions, described by the misalignment angle σ, we take into account the solar divergence and others misalignment phenomena like scattering effects, random tracking errors and the collectors manufacturing tolerances (slope errors). We studied the optical behaviour of the model setting σ equal to 0.25°, 0.75°,1° and 1.25°. The first value represents the circumstance with the effect of solar divergence only, the last value is an extreme working conditions.
In order to evaluate the performance of the concentrator, an optical efficiency was defined:

$$\eta_o = \frac{P_a}{P_p}$$

where P_a is the energy [W] hitting the absorber and P_p is the energy [W] reaching the reflective area.

3. The preliminary study

The first analysis was conducted fixing the absorber diameter equal to 33,7 mm which is a commercial standard. Consequently we modified the focal length and the chord for different tilt angles. We note that, considering only the solar divergence, the optical efficiency is independent of the two parameters in the analysis ranges. For σ equal to 0.75° and 1.25°, instead, we report the diagrams of Fig. 4 (a,b).



(a) (b)

Fig. 4 - The optical efficiency as a function of the chord and the focal length for σ equal to 0.75° (a) and 1.25° (b).

As can be seen the performances grow with the reduction of both focal length and chord but the first width in more critical.
Consider now the configuration with the chord of 2000 mm (higher concentration factor). In this case we found that good performances (η_o = 92.15%) can be reached for tilt angle equal to 1.25° if the focal length is next to 500 mm (Fig. 5).
That is in agreement with the geometrical considerations of the previous section because *f/c* is 0.25. The efficiency loss is due to the absorber diameter. Using the geometrical concentration ratio definition this should be 43,6 mm to ensure that all the rays are intercepted (η_o = 95%).

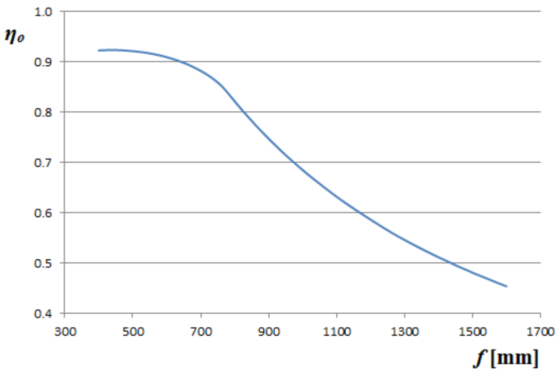


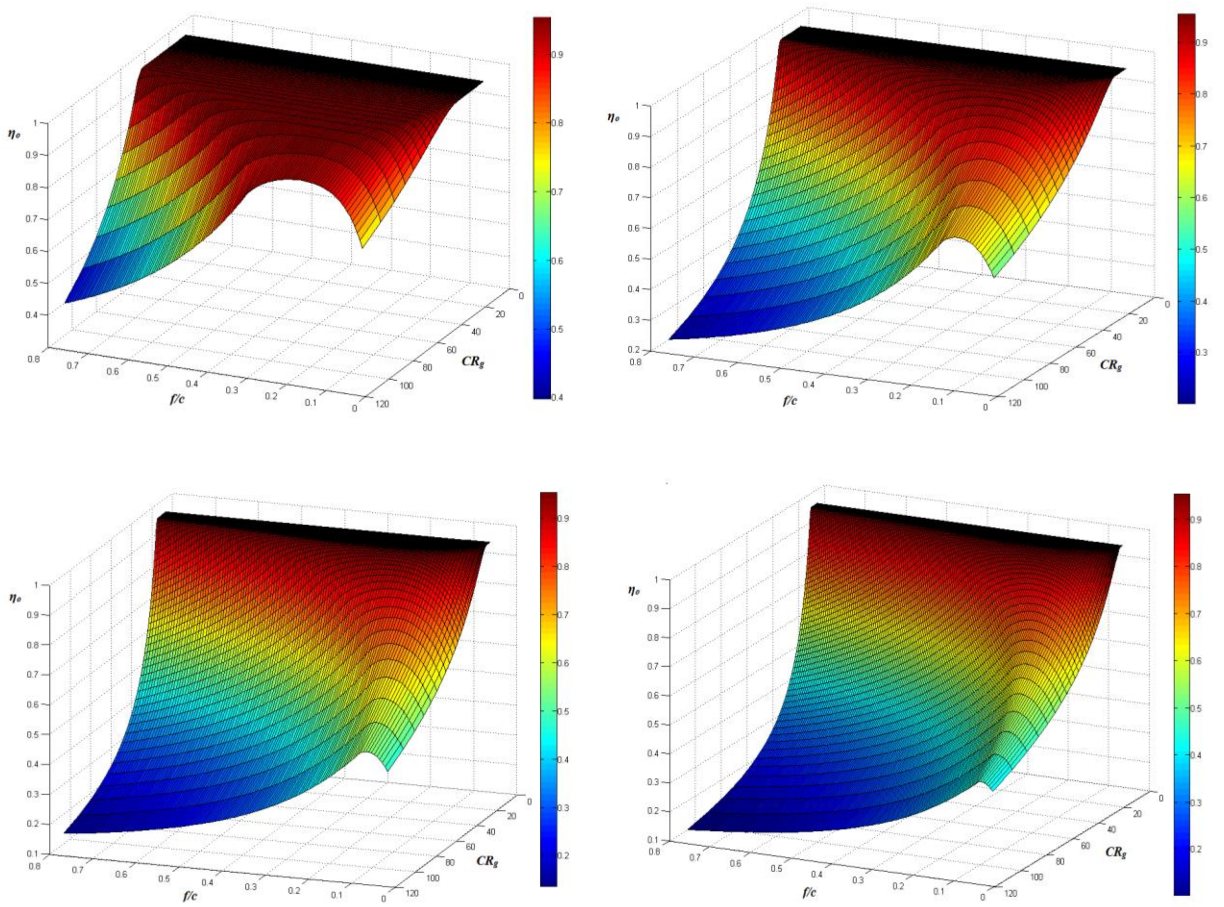
Fig. 5 - The optical efficiency as a function of the focal length for σ equal to 1.25°.

4. The dimensionless analysis

In order to generalize the investigation and understand the optical behavior of a parabolic collector outside the geometrical ideal conditions a further study was conducted. In this section we are interested to optimize the concentrator shape and manage how it is possible to gain medium concentration factors monitoring the efficiency losses.

Some dimensionless parameters were used to describe the collector profile and characteristics. In particular we referred to the focal length-chord ratio, the geometrical concentration ratio and the optical efficiency.

In fig. 6 we show the optical efficiency trends as a function of *f/c* and CR_g for different tilt angles. At first we can say that the last parameter is really significant: the design of medium concentration ratio collectors brings the devices to be very sensitive to the misalignment phenomena in a small range for the tilt angles.



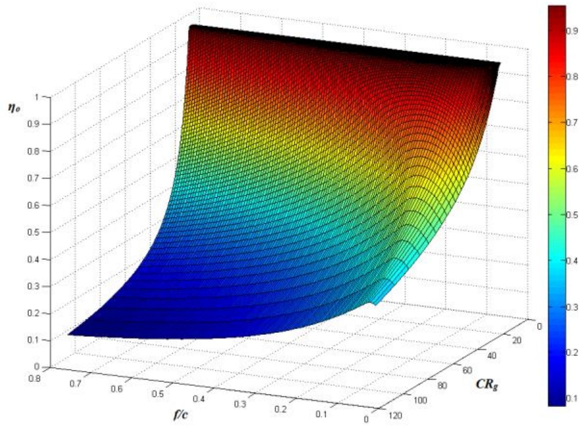


Fig. 6 - The optical efficiency as a function of *f/c* and CR_g for σ equal to 0.25°, 0.5°, 0.75°, 1°, 1.25° respectively.

Then there is another important aspect coming out: constantly checking good performances (η_o > 80%), the best configurations are not the same predicted by the simple geometrical calculations (*f/c* = 0.25 , φ = 90°).
We found that the parabola's curvature should be wider. In particular we aimed the rim angle values from 104° to 112° (*f/c* from 0.194 to 0.169) varying σ from 0.25° to 1.25°.
With this values we can obtain the relative maximum concentration ratios 113, 71, 45, 35, 29 (Fig.7). It is clear that, worsening the boundary conditions, the *f/c* ratio should be gradually reduced to keep higher concentration levels.

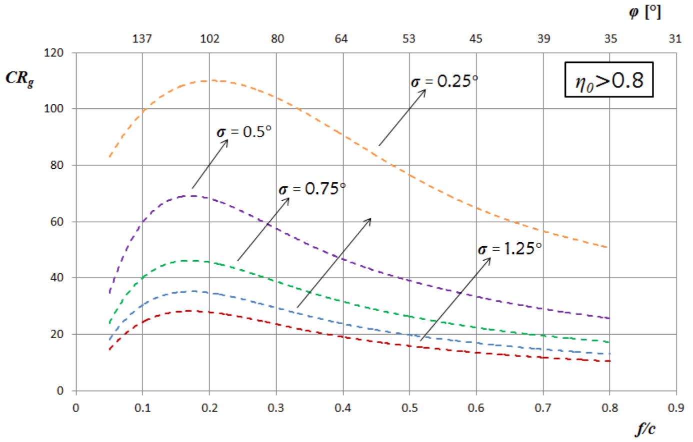


Fig. 7 - The concentration ratio as a function of *f/c* (φ) for σ equal to 0.25°, 0.5°, 0.75°, 1 and 1.25° fixing the optical efficiency up to 0.8.

5 - Conclusions

The proposed study shows how to design a parabolic solar concentrator starting from some boundary conditions and targets. The main important aspect is that there are different optimal configurations for different external constrains.
In particular the random misalignment errors was taking into account and a wide variation on the performances was found depending on them.
From the non-dimensional analysis we deduce that varying the parabolic profile (through the focal length-chord factor or the rim angle) the optical efficiency and the concentration power can be optimized for every external constrains setting.
In non-ideal cases the theoretical rim angle value 90° (*f/c* = 0.25) is not the best: imposing good performance (η_o > 0.8) and different tilt angles (0.25°÷1.25°) it should be increased from 104° to 112° in order to reach the relative maximum concentration factor (Tab. 1).

	$\eta_o > 0.8$		
σ [°]	φ [°]	f/c	CR_g
0.25	104	0.194	113
0.5	106	0.188	71
0.75	108	0.181	45
1	110	0.175	35
1.25	112	0.169	29

Table 1 - Optimal values for the rim angle, the focal length-chord ratio and CR_g imposing the optical efficiency up to 0.8.

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